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EXPERIMENTAL EVALUATION OF SAMPLING BIAS IN NATURALLY SEEDED FL--ETC(U)
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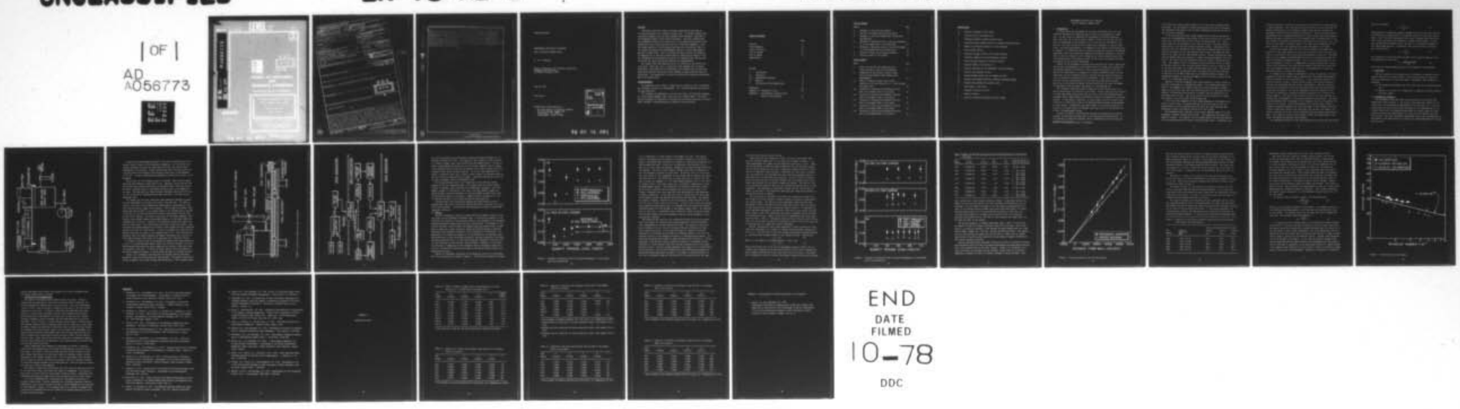

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER AFOSR-TR-78-1214	2. GOVT ACCESSION NO. / 3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EXPERIMENTAL EVALUATION OF SAMPLING BIAS IN NATURALLY SEEDED FLOWS	5. TYPE OF REPORT & PERIOD COVERED FINAL 1 Apr 77 - 31 Jan 78
	6. PERFORMING ORG. REPORT NUMBER EN-78-ME-1
7. AUTHOR(s) W G TIEDERMAN	8. CONTRACT OR GRANT NUMBER(s) AFOSR-77-3298
9. PERFORMING ORGANIZATION NAME AND ADDRESS OKLAHOMA STATE UNIVERSITY SCHOOL OF MECHANICAL AND AEROSPACE ENGINEERING STILLWATER, OKLAHOMA 74074	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 2307D9 61102F
11. CONTROLLING OFFICE NAME AND ADDRESS AIR FORCE OFFICE OF SCIENTIFIC RESEARCH/NA BLDG 410 BOLLING AIR FORCE BASE, D C 20332	12. REPORT DATE June 1978
	13. NUMBER OF PAGES 23
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)	15. SECURITY CLASS. (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

19 18 AFOSR 9 Final rept. 14 15 17 D9 16 11 23 Jun 78 12 34p.

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

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18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

LASER VELOCIMETER

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Individual realization laser velocimeter measurements were made in the viscous sublayer of a turbulent channel flow. The Doppler signals were recorded on magnetic tape and then processed with systematic variations in the triggering levels in the counter processors. Naturally seeded flows were modeled by using 0-10 μm test dust for scattering centers while flows seeded with 5-10 μm test dust were used as a controlled comparison. Both the number density of the scattering particles and the detection level of the counter processors were independently varied to yield a wide range of particle arrival rates. Also, an attempt

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Report EN-78-ME-1

EXPERIMENTAL EVALUATION OF SAMPLING BIAS IN NATURALLY SEEDED FLOWS

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June 23, 1978

Final Report

Prepared from work sponsored by

Air Force Office of Scientific Research
Air Force Systems Command USAF
Bolling AFB, D.C. 20332
Grant Number: AFOSR 77-3298

ACCESSION for

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ABSTRACT

Individual realization laser velocimeter measurements were made in the viscous sublayer of a turbulent channel flow. The Doppler signals were recorded on magnetic tape and then processed with systematic variations in the triggering levels in the counter processors. Naturally seeded flows were modelled by using 0-10 μm test dust for scattering centers while flows seeded with 5-10 μm test dust were used as a controlled comparison. Both the number density of the scattering particles and the detection level of the counter processors were independently varied to yield a wide range of particle arrival rates. Also, an attempt was made to prove the existance of sampling bias in naturally seeded flows by comparing the slopes of both the unweighted and the weighted (corrected for sampling bias) velocity profiles with the slope deduced from pressure drop measurements.

The results show that sampling bias is not effected by the particle arrival rate. There was, also, no indication that sampling bias is either eliminated or decreased due to differences in the probability for detecting small particles that are moving slowly compared to small particles that are moving fast. The comparisons of velocity gradients with pressure drop measurements were inconclusive.

ACKNOWLEDGEMENTS

The assistance of Mr. David G. Bogard and Mr. Michael E. May in conducting this research is gratefully acknowledged. Mr. Jeff Moon assisted with some of the data reduction.

This research was sponsored by the Air Force Office of Scientific Research, Air Force Systems Command, USAF, under Grant No. AFOSR-77-3298. The United States Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation hereon.

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NOMENCLATURE

D_H	Hydraulic diameter of the channel
f	Friction factor (see Equation 6)
L	Streamwise distance between pressure taps
l_s	Average distance between particles yielding validated signals
N	Number of individual samples in a data ensemble
U_a	Mass average velocity
U_B	Frequency average estimate of the mean velocity
U_i	Individual sample of the instantaneous velocity
U_c	Period average estimate of the mean velocity
Re	Reynolds number (see Equation 7)
s_B	Standard deviation of the unweighted velocity ensemble
T	Time for the ensemble of data
T_D	Average Doppler period for an ensemble of data
T_s	Average time between particles yielding validated signals
ΔP	Pressure drop between the pressure taps
λ	Wave length of the laser
ν	Kinematic viscosity of water
ρ	Density of water
θ	Angle of intersection between the laser beams

EXPERIMENTAL EVALUATION OF SAMPLING
BIAS IN NATURALLY SEEDED FLOWS

I. INTRODUCTION

In recent years the development of the laser velocimeter (LV) as a non-intrusive instrument for measuring fluid velocity has proceeded at a rapid rate. As one can see by comparing the proceedings of technical meetings held a few years ago, such as those at Purdue in 1972 (1)* and 1974 (2) with those at Copenhagen (3) and Minnesota (4) in 1975 and the 1976 AGARD conference (5), the state-of-the-art has evolved from an emphasis on optical, electronic, and system development to an emphasis on utilization and interpretation. In addition to a substantial base of expertise about the electronic and optical subsystems, there now are several commercial instruments available to the user. Even so, the full potential of LV systems has not been realized because both the interpretation of the signals as well as the correct application of these instruments are not yet well understood.

Several of the fundamental problems associated with the correct application and accurate interpretation of the signals from a LV system occur because the velocimeter measures the velocity of small particles entrained in the flow. Usually the investigator is attempting to acquire information about the fluid velocities and this information must be deduced from the particle velocities that are detected and measured by the velocimeter. This report is concerned with the accurate interpretation of fluid velocities when the scattering particles are accurately following the fluid motion and the laser velocimeter is operating in the individual realization or counting mode (6).

The individual realization mode of operation is the natural result of a dilute concentration of particles in the fluid. This is typically the situation in large wind tunnel applications such as those at the Arnold Engineering Development Center (AEDC) where the airflow is usually not seeded with scattering centers. In this mode of operation, an output signal occurs only when a particle that is sufficiently large to be detected passes through the measurement or probe volume. Consequently the output signal is discontinuous and the occurence of an output signal is dependent upon the arrival of a detectable particle in the measurement volume.

Because the signal is discontinuous, statistical methods must be used to estimate the desired quantities such as the time-average fluid velocity. If the sampling is random and unbiased, then an unweighted statistical analysis

*Numbers in parenthesis refer to references.

of the data will yield accurate estimates of the mean and root-mean-square velocities. If the sampling is biased because some velocities are detected more frequently than others, then suitable weighting factors must be used in the statistical analysis.

It has been postulated that biased sampling occurs when the scattering particles are homogeneously distributed in the fluid and when there is equal probability that each particle will yield a validated signal (7). Under these conditions the probability for a particle being in the probe volume is proportional to the flow rate through the probe volume. Consequently more particles will flow through the probe volume and be detected when the fluid velocity is higher than the time-average fluid velocity than when the fluid velocity is lower than the time-average velocity. Several analyses have been made and methods have been proposed to correct biased measurements (7,8,9,10, 11,12). The corrections are significant when the velocity fluctuations are large. For example, errors in estimates of mean velocities can be as large as 10% while errors in the root-mean-square velocity can be as large as 100% in the near wall region of a bound turbulent shear layer (12). The problem is even more severe in separated flows. Re-evaluation of LV data from the 1T bump test at the AEDC showed that the differences between weighted and unweighted estimates of the mean streamwise velocity was on the order of 100 ft/sec. in a separated region (13).

However, it has been suggested that biased sampling is either totally or partially eliminated by a compensating effect. This compensating effect is based on the argument that signals from slower particles produce a higher signal to noise ratio than that from faster particles (14) and hence the probability for detecting slow particles is greater than the probability for detecting fast particles. One of the objective of this study was to determine whether or not this effect could be detected.

It has also been suggested (8) that biased sampling is influenced by the particle arrival rate. A second objective of this study was to vary the number density of the scattering particles while the flow conditions were maintained constant and thereby directly test this concept.

The experiments were conducted in the viscous sublayer region of a fully developed, turbulent channel flow of water. This apparatus was chosen for a number of reasons. For example, both the number density and size distribution of the scattering particles could be controlled and varied. In addition, the turbulence intensity is high in the sublayer and the effect of biased sampling is easily detected. Also, the velocities are relatively low and therefore the Doppler frequencies can be recorded on magnetic tape and then reduced with systematic variations in the processor electronics. Finally the water channel measurements are a reasonable simulation of transonic wind tunnel measurements because the signal-to-noise ratio of the Doppler signal is proportional to the laser power and inversely proportional to the speed of the particle (15). This ratio of laser power to particle speed is the same order of magnitude in the water channel and in the transonic wind tunnel experiments at the AEDC.

The naturally seeded flow conditions in the transonic wind tunnel were simulated in the water channel by using 0-10 μm particles of AC Fine Test Dust. This is a variation of the 5-10 μm seed used previously (12,16,17). The upper limit of 10 μm diameter was maintained so that all of the particles were capable of accurately following the flow. The 0-5 μm fraction was added to the seed to determine if there is a compensation to biased sampling due to variations in the probability for detecting the smaller particles which yield signals with marginal signal-to-noise ratios. Flows seeded with 5-10 μm test dusts were used for a controlled comparison.

An attempt was also made to experimentally verify the existance of biased sampling in naturally seeded flows by making laser velocimeter measurements at several locations in the viscous sublayer. In this near-wall region of the flow the velocity profile is linear and the slope of the velocity profile at the wall was determined from the velocity measurements. Two data reduction techniques were applied to the laser velocimeter data and thus two different slopes were determined. One was an unweighted statistical analysis of the data and the second was a weighted statistical analysis that "corrects" for biased sampling. The slope of the velocity profile at the wall was also estimated from a measurement of the pressure gradient along the wall. The gradient was deduced from a measurement of the pressure drop over an eighteen inch length of the channel. Under the assumption that the wall shear stress is constant around the perimeter and along the length of this eighteen inch long control volume which contains the velocimeter test section, the slope of the velocity profile at the wall can be determined from the pressure drop measurement. This slope was taken as the standard to which the slopes given by the laser velocimeter measurements were compared.

The unweighted estimates of the time-average fluid velocity were calculated from the expression

$$U_B = \sum_{i=1}^{N} U_i/N. \qquad (1)$$

This estimate is called the frequency average velocity because each velocity realization U_i is proportional to the Doppler frequency of the laser velocimeter. Since the laser velocimeter was a single component device and since both counter processors were designed to analyze a fixed number of cycles, the one-dimensional weighting factor was used in the weighted estimates of the time-average velocity. Consequently the corrected velocity estimate was calculated from

$$U_c = N/\sum_{i=1}^{N} U_i. \qquad (2)$$

This estimate is called the period average velocity because Equation 2 can be manipulated into the form

$$U_c = \frac{(\lambda/2)\sin(\theta/2)}{T_D} \qquad (3)$$

where T_D is the average Doppler period for the ensemble of realizations.

II. OBJECTIVES

The basic purpose of this research was to determine the methods and procedures required to accurately deduce fluid velocities from the particle velocities measured by a laser velocimeter. Experiments were conducted to determine:

(1) How sampling bias depends upon the arrival rate of scattering centers, and

(2) Whether or not there is a compensation to sampling bias when flows are naturally seeded.

III. EXPERIMENTAL APPARATUS

The measurements were made using the recirculating flow loop and two-dimensional shown in Figure 1. The acrylic, two-dimensional channel was 72 inches long, 12 inches high and approximately one inch wide (17). A section containing baffle plates and screens was added at the downstream end of the channel (16) so that the downstream head would be constant enough to allow accurate pressure drop measurements to be made over the eighteen inch long test section. The laser velocimeter measurement station was approximately in the middle of the test section at a position 55 inches downstream of the Borda type entrance.

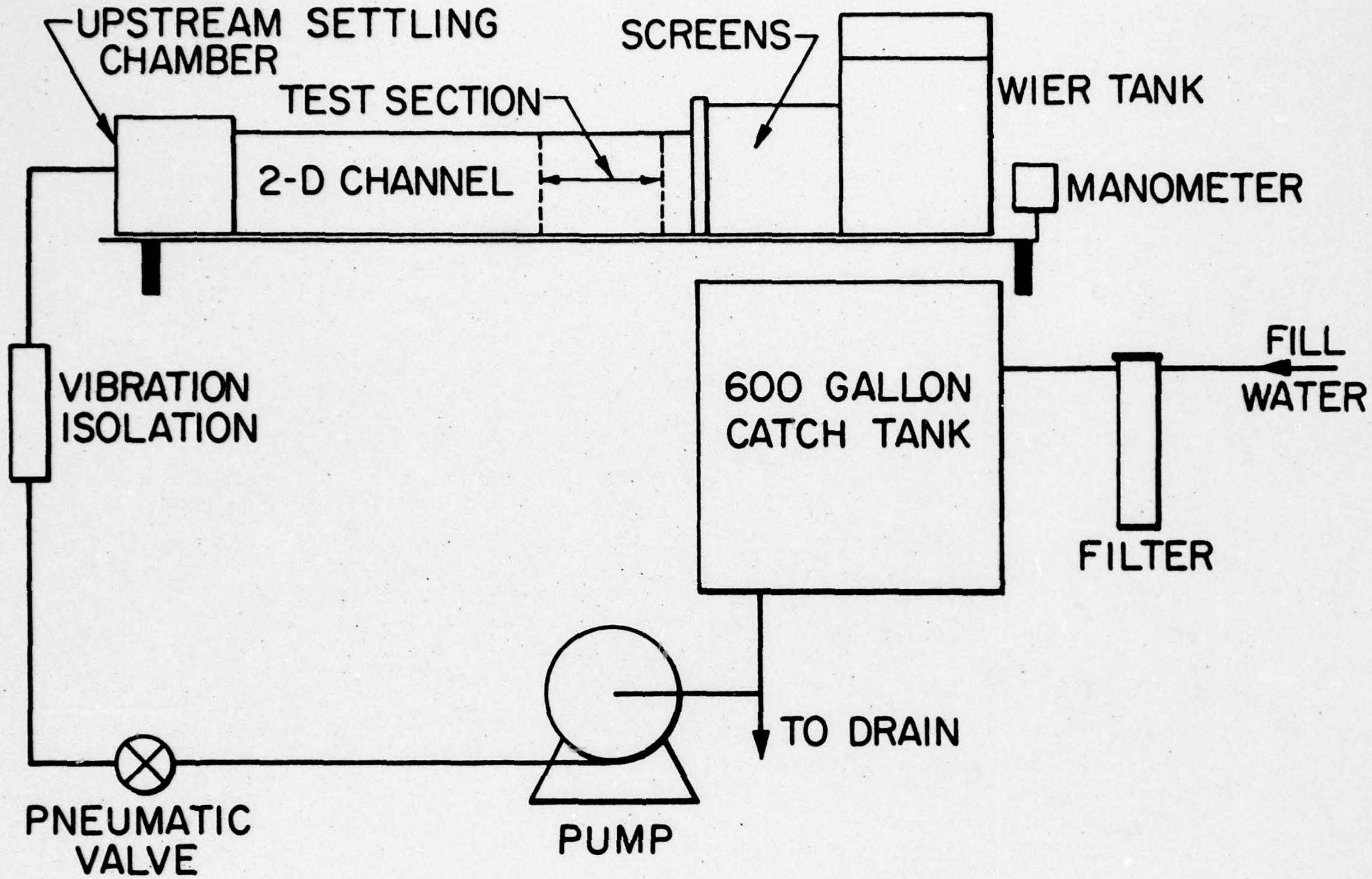

FIGURE 1. Schematic of Flow Loop and Channel

Pressure drop measurements were made at the vertical mid-section of the channel using a Gilmont G-1500 Micrometric Manometer. The two 0.0625 inch diameter pressure taps were 18 inches apart with the first tap 48 inches downstream of the entrance. Carbon tetrachloride with a specific gravity of 1.59 was used as the manometer fluid giving a sensitivity of approximately $\pm 10^{-5}$ psi. A static calibration was performed to verify the accuracy of the manometer.

Notice that all of the make-up water is filtered. These filters remove particles with diameters larger than 0.5 μm. Therefore, since the flow loop and channel were constructed entirely of stainless steel, brass and plastic the water contained almost no detectable particles prior to the addition of the seed. The seed particles added during an experiment were either 0-10 μm or 5-10 μm particles classified from AC-Fine Test Dust. This dust is predominately sand.

The channel and the laser velocimeter were especially designed to permit velocity measurements to be made very close to the wall (18). As shown in Figure 2, the walls of the channel were bowed inward by approximately 0.060 inch along the entire length of the channel. This allowed the incident laser beams which were parallel to the channel walls to be traversed all of the way to the wall at the vertical mid-section without interference from the lower portion of the channel. The spatial resolution of the single component, dual-scatter LV was optimal because the minimum dimension of the probe volume was perpendicular to the wall. Moreover, two cylindrical lenses were used to expand the laser beams in one plane before they were focused and crossed. This decreased the minimum dimension and yielded a probe volume that had a dimension normal to the wall of 0.0024 inches. An optical technique for cancelling the pedestal frequency was used in the receiving optics (19). This technique was necessary since the common pedestal and Doppler frequencies that occurred in this highly turbulent flow could not be separated by an electronic filter.

As shown in Figure 2 both the receiving and sending optics were mounted on a single traversing mechanism which travels in a direction normal to the wall. This mechanism positioned the probe volume with an accuracy 0.0001 inch from one location to the next. It should be noted, however, that the position of the probe volume with respect to the wall was not known to the same accuracy.

Figure 3 is a schematic that shows how the signals from the two photomultiplier tubes were differenced and then recorded. The Doppler signals were stored on magnetic tape using an Ampex FR1300 tape deck. The recorded signals

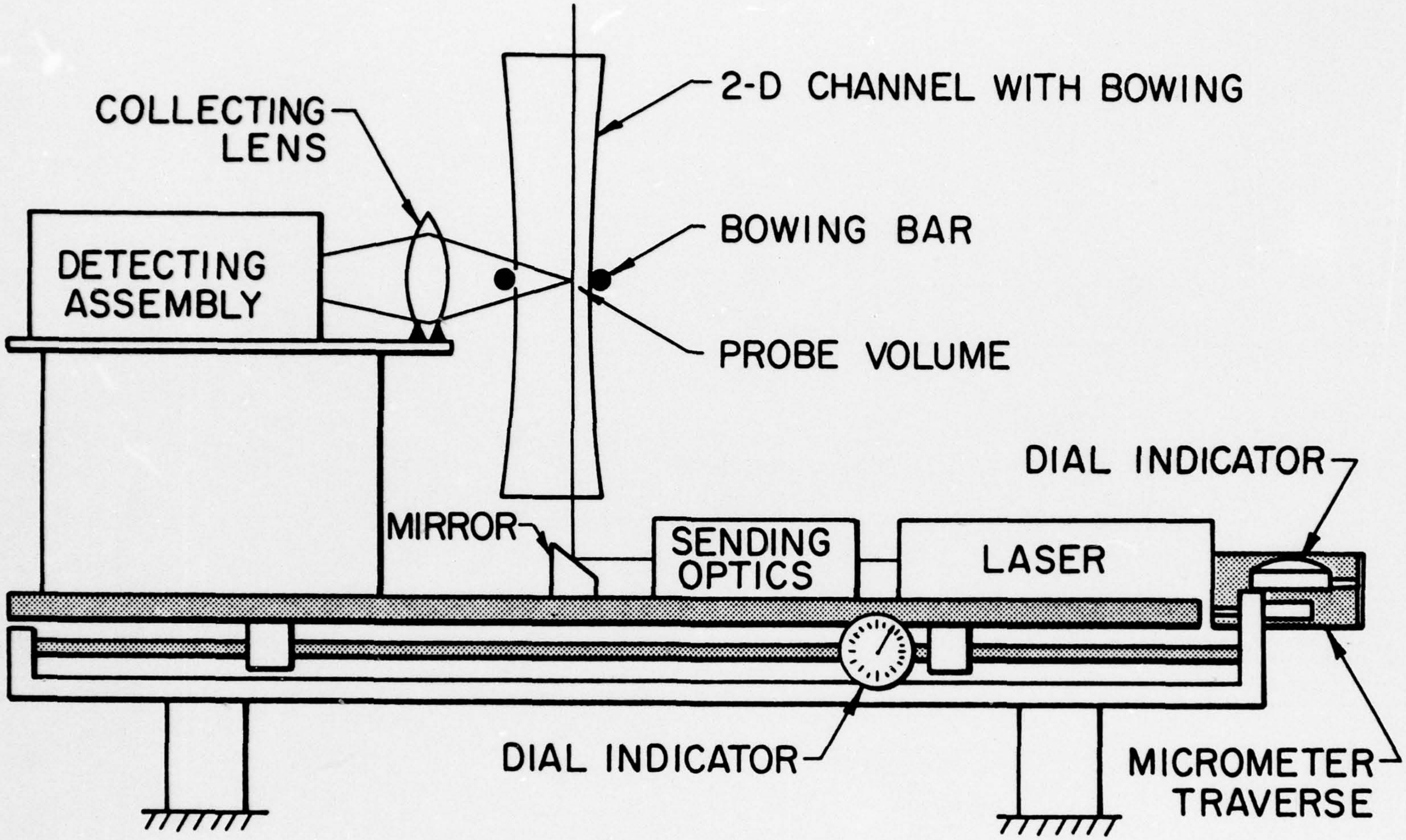

FIGURE 2. End View of Channel and Laser Velocimeter

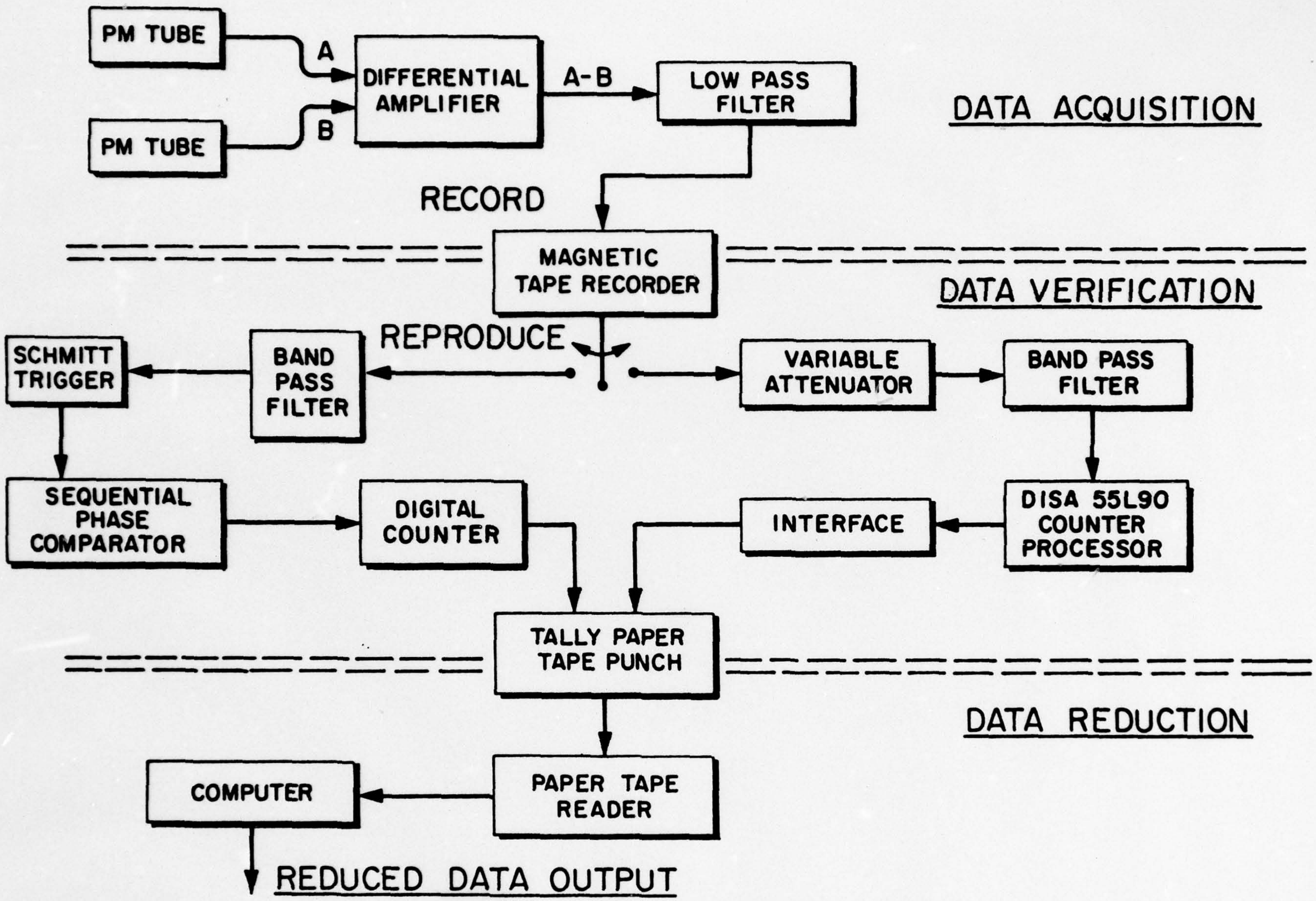

FIGURE 3. Schematic of the Data Acquisition, Verification and Reduction

were later processed using two different counter processors designed for individual realization LV data. The Sequential Phase Comparator (SPC) operates on a Schmitt trigger pulse train derived from the Doppler signal. The device uses a system whereby the period of one cycle from a Doppler burst is sequentially compared with the time for the previous cycle from the same burst until a signal of ten cycles has been analyzed. If all ten time comparisons are within a tolerance level, then a digital counter outputs the average period for the ten cycles for subsequent data storage. A detailed description of the SPC is given by Salsman, Adcox, and McLaughlin (20).

The second processor used in this study was a DISA 55L90 LDA counter operated in the 5/8 comparison mode. This counter uses an internal Schmitt trigger to develop a pulse train which is subsequently analyzed. Since this Schmitt trigger is activated at a set level, the input Doppler signal was passed through a variable attenuator so that the Schmitt trigger level could be varied with respect to the signal. Compute accuracy settings of 1.5 and 3.0 percent were used on the counter during the data reduction.

Verified signal from both data processors was digitized and stored on punched paper tape using a Non-Linear Systems 2607 Serial Converter and a Tally P-120 Tape Perforator. This data was then analyzed on a Hewlett Packard 9820 computing calculator.

IV. RESULTS

One major advantage in having an analog tape of the Doppler signals is that the output can be processed in different ways. Of particular interest in this study was the influence of the detection level on the estimates of the frequency average and period average velocities from a data record. The purpose in varying the electronic level at which the Doppler signal was detected was to determine if there was a range of particle sizes that yielded signals of marginal amplitudes with systematic variations in the probability for detection. The hypothesis to be tested was whether or not the probability for detecting slow moving particles in this size range was greater than the probability for detecting fast moving particles. If this occurs then the estimates of the mean velocity will decrease as the detection level decreases. Moreover, if the effect is sufficient to compensate for bias sampling then the frequency average velocity at a low detection level will be equal to the period average velocity at a high detection level.

Results for systematic variations in the detection level for a flow seeded with 5-10 μm particles are shown in Figure 4. This data was originally recorded

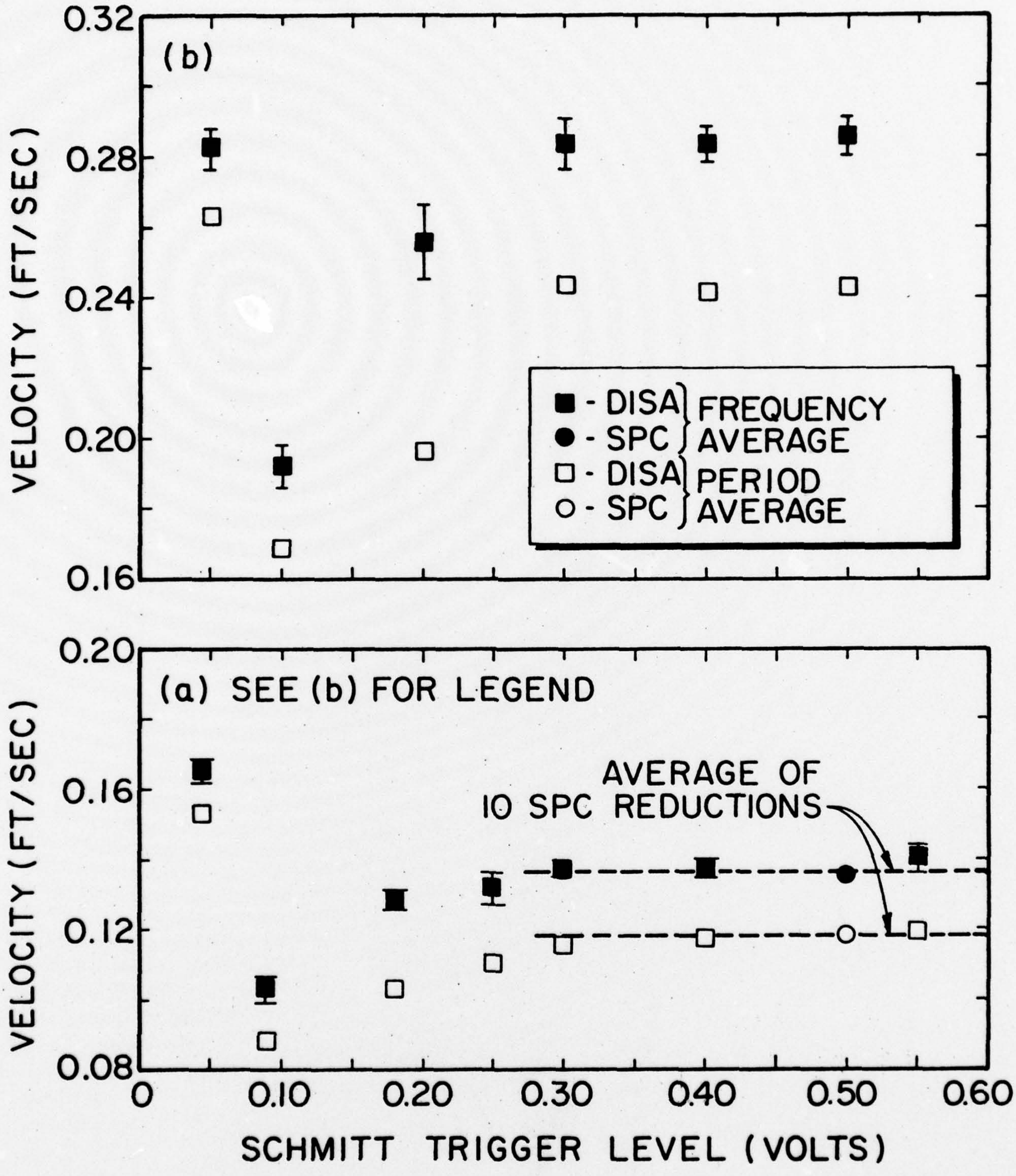

FIGURE 4. Influence of Detection Level on Velocity Estimates in a Flow Seeded with 5-10 μm Particles

at y = 0.0058 and y = 0.0106 inches in Run Number BC-3 (16). The voltage given in the Figure was the setting of the Schmitt Trigger for the SPC processor. The signals were attenuated to produce an equivalent setting when the DISA processor was used. Notice that for detection levels greater than or equal to 0.3 volts both the frequency average and the period average velocities are constant. The bars on the frequency average velocities are estimates of the 95% confidence intervals for this data. As shown in part (a) of the Figure, this result is also independent of the counter used to process the signal. (The data for the 9 SPC reductions not shown explicitly in Figure 4 (a) appear in Table A.1, Appendix A.) For these Doppler signals, the 0.3 volt level is slightly above a continuous signal that is probably a combination of noise and weak Doppler signals. Most operators of individual realization systems would choose to operate their velocimeter near this detection level in an attempt to maximize their data rate while also maintaining a high percentage of signal validations. As the detection level is raised only the larger amplitude Doppler signals are detected and the data rate declines. For example, the number of signals validated by the SPC processor varied from 2026 at the 0.3 volt level to 272 at the 1.8 volt level. At the 0.3 volt level the average time between validated signals was 0.35 seconds while the average time between validated signals was 2.62 seconds at the highest trigger level. The important point is that over a considerable range of detection level the period average and frequency average velocities estimated from the various ensembles of realizations were constant.

The detection level was also set considerably below the intuitive optimal level even though the validation percentage dropped well below the minimum level recommended for reliable operation by DISA. The reason for doing this was an attempt to extract velocity estimates from the continuous but lower level signals and noise. As the detection level was lowered the velocity estimates first decreased as the number of validated signals in the very low frequency portion of the ensemble increased by a disproportionate amount. The resulting histograms were bimodal in shape and physically unrealistic. Further decreases in the detection level yielded an increase in the average velocity estimates to a level markedly above the accurate estimate given by the higher detection levels. From our limited experience this seems to be a characteristic of the processor. We used this combination of low validation percentage and simultaneous disproportionate increase in the number of validated signals in the very low frequency range as indication that the detection level was lower than that which yields accurate results.

Similar results were obtained at three y location in Run Number 3300 when the flow was seeded with 0-10 μm particles as shown in Figure 5. For these measurements the lowest accurate detection level was 0.4 volts. Again the two processors yielded the same estimates of both the frequency average and the period average velocity over a substantial range of detection levels. This is an important result because it indicates that there was no evidence that the probability for detecting slow particles had increased relative to the probability for detecting fast particles. With this broad size distribution of seed particles it had been thought that the average velocity estimates might decrease as the Schmitt trigger was lowered. This did not occur in the operational range of detection for the DISA and SPC processors in this experiment. The experiment is definitive because for the 0-10 μm seed the number of particles in the marginally detectable size range must increase as the detection level is lowered.

The arrival rate of particles that yield valid signals was varied over a wide range in the water channel by simply varying the amount of seed added to the filtered water. The results for two experiments where the flow rate, measurement location and detection level were held constant while the amount of seed particles was varied in steps are shown in Table 1. In reducing the tapes from both experiments, the detection level was set well above the noise where Figures 4 and 5 have shown that the velocity estimates are not effected by the detection level. There are two types of comparisons that can be made from this data. First, by considering only the results from runs with 5-10 μm seed, one can see that an eight fold variation in arrival rate of the same type of particles does not change the velocity estimates.

Another interpretation that allows comparison of these results with those from other experiments is to deduce an average distance between validated particles, l_s. This was done by using the average time between validated signals, T_s, and the period average estimate of the average velocity. Specifically

$$T_s = T/N \tag{4}$$

where N is the number of validated signals in time T and

$$l_s = U_c T_s . \tag{5}$$

Using results from both of the 5-10 μm experiments shown in Table 1 one can conclude that estimates of the mean velocity will not vary as the average distance between validated particles varies from 0.34 to 4.42 feet. This range may be expanded by using the results from Figure 4 where the velocity extimates

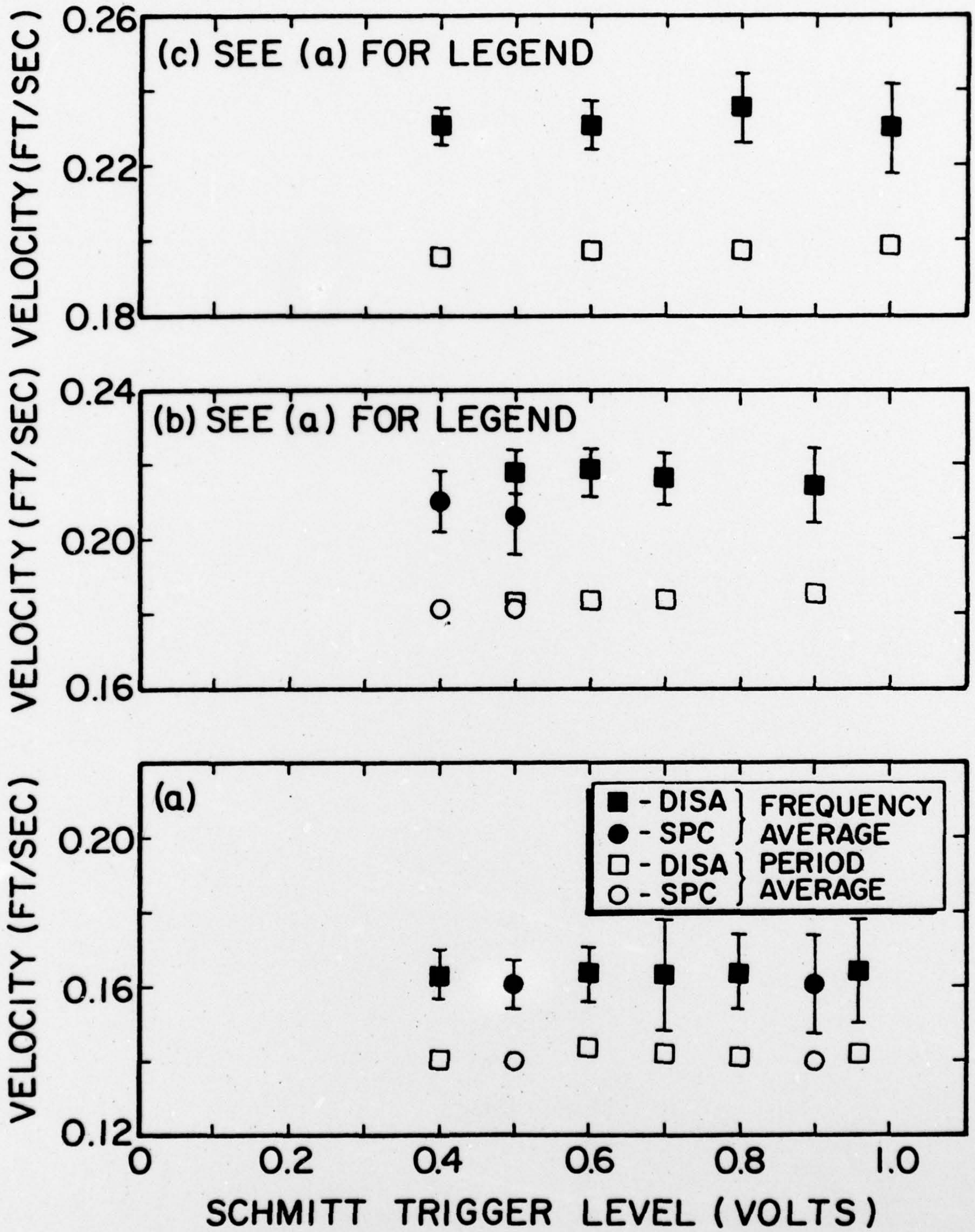

FIGURE 5. Influence of Detection Level on Velocity Estimates in a Flow Seeded with 0-10 μm Particles

Table 1. Effect of the Type and Concentration of Seed Particles on the Velocity Estimates

Run Number	U_B (ft/sec)	U_c (ft/sec)	T_s (sec)	l_s (ft)	Type and amount of seed in 300 gallons
7107	0.257 ± 0.016	0.223	19.80	4.42	1/8 gm; 5-10μm
7108	0.257 ± 0.010	0.225	2.06	0.464	1 gm; 5-10μm
7109	0.256 ± 0.012	0.219	2.56	0.560	1 gm; 5-10μm 1 gm; 0-10μm
7110	0.263 ± 0.013	0.227	2.05	0.464	1 gm; 5-10μm 2 gm; 0-10μm
7113	0.247 ± 0.010	0.217	1.55	0.336	1 gm; 5-10μm 3 gm; 0-10μm
9002	0.493 ± 0.013	0.444	6.00	2.66	1/4 gm; 5-10μm
9003	0.490 ± 0.009	0.434	0.784	0.340	1 gm; 5-10μm
9005	0.480 ± 0.010	0.434	0.824	0.360	1 gm; 5-10μm 1 gm; 0-10μm

were constant over a wide range of detection levels. As mentioned earlier the number of particles detected per unit time increases as the detection level is decreased. For the results in Figure 4 (a), the velocity estimates were constant as the average distance between particles varied from 0.043 to 0.31 feet. Combining these results for 5-10 μm particles from Figure 4 and Table 1 we conclude that estimates of the mean velocity will not vary as the average distance varies from 0.043 to 4.42 feet or from distances that range from ½ to 48 times the width of the channel.

The second comparison is between experiments where 1 gram of 0-10 μm seed was added to fluid that already contained 1 gram of 5-10 μm seed. Notice that there is a surprising increase in time between validated signals when the 0-10μm seed is added (compare Run 7109 with 7108 and Run 9005 with 9003). The explanation for this increase is simply that the S/N ratio is lower with the broader distribution of particle sizes and hence the percentage of signals validated by the counter processor decreases.

Several experiments were performed in which the slope of the velocity profile was determined using both laser velocimeter measurements and simultaneous measurement of the pressure drop in the water channel. Figure 6 is an example of the laser velocimeter data showing the two different slopes which can be deduced depending on whether the data is frequency averaged or period averaged. Note

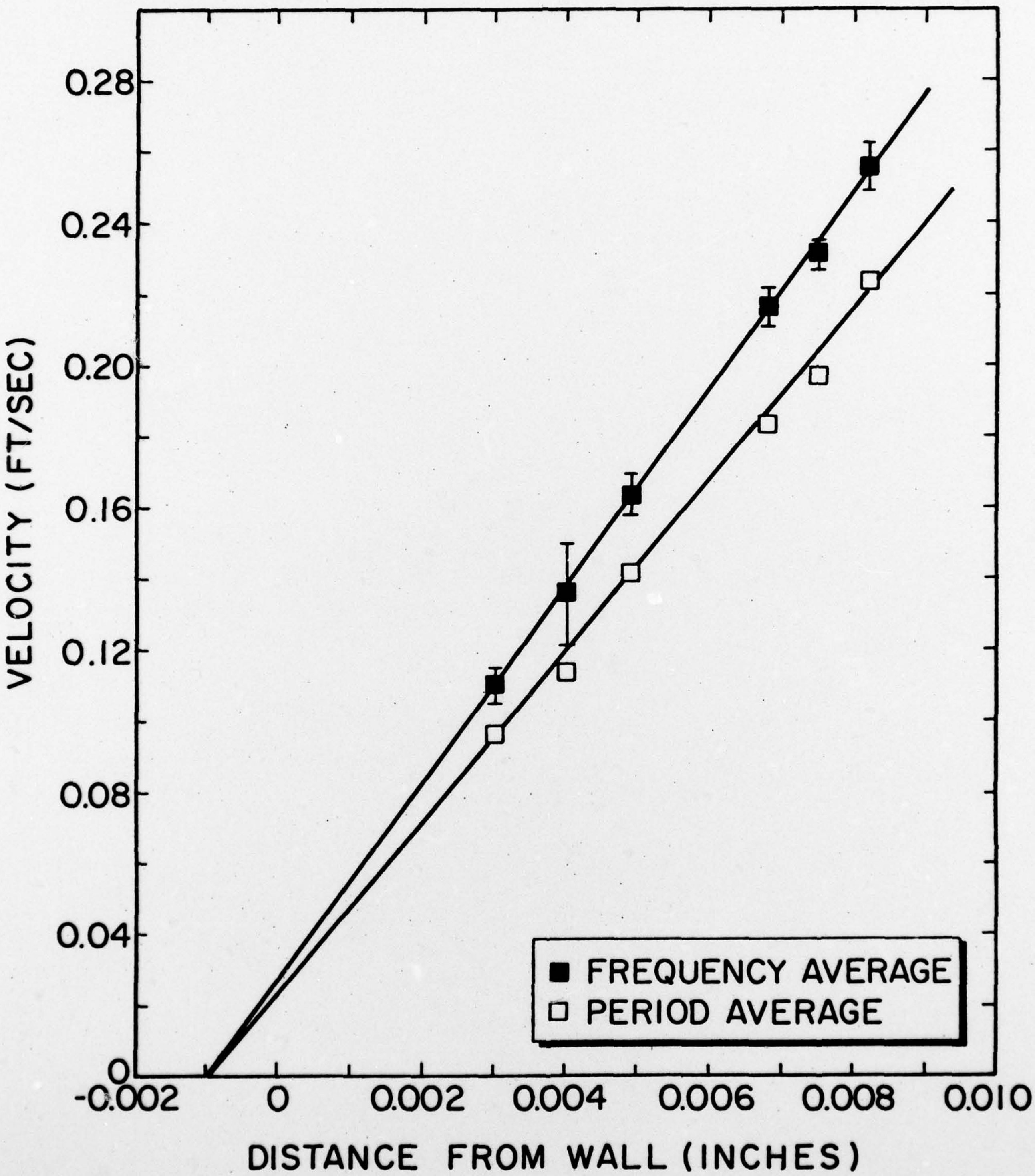

FIGURE 6. Velocity Profiles in the Viscous Sublayer

that the two lines intersect the axis at a negative distance from the wall. This is merely indicative of a slight error in the initial placement of the probe volume with respect to the wall. More significant is the linearity of both the frequency averaged and period averaged data which results in small uncertainty bands on the slopes estimated from this data. One reason that the results are so linear is that the viscous sublayer was on the order of 0.012 inches thick. Consequently all six measurements were well within the sublayer.

The results in Figure 6 are typical of all the velocity profile data. The LV data from all of these experiments are tabulated in Appendix A; Tables A.2 to A.6. The velocity gradients deduced from the data in these five experiments are shown in Table 2.

Also shown in Table 2 is the slope of the velocity profile at the wall that is calculated from the pressure drop measurements. In all cases the slope deduced from the pressure drop was larger than the slope given by either reduction of the LV data. In fact, in four of the five cases the slope calculated from the pressure drop was much larger.

The original hypothesis in the design of this experiment was that within the random experimental error of the measurements the slope calculated from the pressure drop would agree with either the slope of the corrected velocities or the slope of the uncorrected velocities. In an earlier experiment (16) conducted with basically the same channel and LV and with 5-10 μm seed, the results were quite different. In that case the slope from the pressure drop

TABLE 2. Comparison of the Velocity Profile Slopes with the Slope Deduced from Pressure Drop Measurements.

Run Number	Type and Amount of Seed	Slope of Velocity Profile at Wall: From U_B Data	From U_c Data	From ΔP Data
3100	1 gm; 0-10 μm	27.2	23.9	28.5
3300	1 gm; 0-10 μm	27.7	24.0	34.2
4000	1 gm; 5-10 μm	26.6	22.8	34.0
5000	1 gm; 5-10 μm	22.0	20.1	28.3
6000	1 gm; 5-10 μm	25.5	23.9	30.0

measurements clearly agreed with the slope of the corrected LV data.

The reason for this difference between previous results (16) and the results for experiments 4000, 5000 and 6000 was explored in great depth. For example, the manometer was calibrated with static water heads measured by a dial indicator; the Doppler constant of the LV was remeasured; all of the previous data (16) were re-evaluated; the bowing of the channel was carefully measured; and a new friction factor, Reynolds number correlation was determined experimentally. These checks showed that when the manometer was clean that its results were reproducible and accurately calculated from the measured deflection of the meniscous and the stated specific gravity of the carbon tetrachloride. The Doppler constant had not changed. However the friction factor, Reynolds number correlation had changed. This change is shown in Figure 7 where Quigley's (16) measurements as well as the more recent measurements are compared to Blasius correlation. For a further comparison, the results from an experiment in a two-dimensional channel flow of air (21) are also shown.

The friction factor plotted in Figure 7 was calculated from

$$f = \frac{(\Delta P/L)\ D_H}{\frac{1}{2}\ \rho\ U_a^2} \qquad (6)$$

where D_H is the hydraulic diameter of the channel. The average velocity, U_a, was calculated from measurements of the flow rate and cross sectional area of the channel. A calibrated catch tank and timer were used to measure the flow rate. The Reynolds number was defined by

$$Re = \frac{U_a\ D_H}{\nu} \qquad (7)$$

It is obvious that the pressure drop in the channel has increased between 1975 and 1977. The reason for this increase has not been clearly identified. The channel walls had low amplitude longitudinal waves above the bowing bar at the conclusion of these latest experiments. One could hypothesize that this warping of the channel might have occurred with age and that it might be significant enough to account for the different results. However, this hypothesis can not be checked in retrospect. In any case the disparity between these latest slopes deduced from these pressure drop measurements and those deduced from LV data make it impossible to use these latest results to confirm whether or not sampling bias effected the velocity data in either the naturally seeded flows or the control seed experiments. Moreover, our inability to replicate

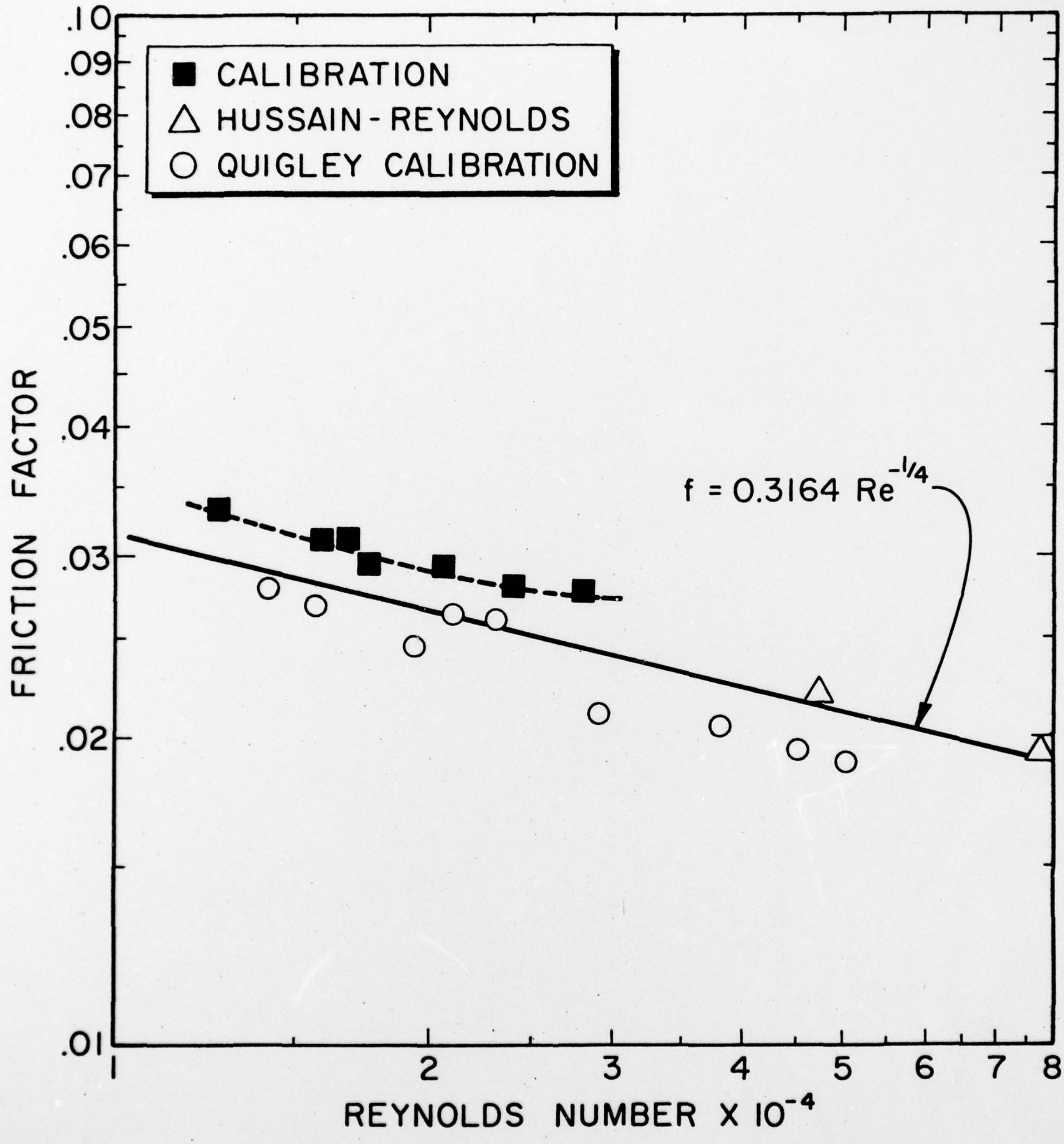

FIGURE 7. Friction Factor in the Channel

earlier experiments with control seed suggest that further experiments with a different apparatus may be needed.

V. CONCLUSIONS and RECOMMENDATIONS

Two types of flow seeding were examined during this study. Naturally seeded flows were modelled by using 0-10 μm test dust while flows with controlled seeding were modelled with 5-10 μm test dust. Two of the experiments listed in Table 1 show the effects of adding 0-10 μm seed to the flow already containing 5-10 μm seed. In effect a controlled seed experiment was transformed to a natural seed experiment with all other variables held constant. When examining the resulting data one finds that the mean velocity, whether frequency averaged or period averaged, did not change when the 0-10 μm seed was added. Also, in Figure 1 (controlled seed) and in Figure 2 (natural seed), both seeding conditions yield consistent mean velocity values over a wide range of Schmitt trigger settings when the detection level is above the noise levels. The combination of these results leads to the conclusion that individual realization laser velocimeter measurements will yield the same result whether the flow is seeded with a broad range of particle sizes or with a narrow range of particle sizes. These results also show that there was no measurable compensation for bias sampling due to differences in the light intensity scattered from slow and fast moving particles.

Several experiments were designed to investigate the effect of particle arrival rate upon sampling bias by varying the seed density in the flow over a wide range. The effect of particle arrival rate was further studied in flows with constant seed density by varying the number of validated signals through adjustments in the Schmitt trigger level. All the experimental data indicates that the particle arrival rate does not influence either the frequency average or the period average estimates of the mean velocity. Hence the particle arrival rate does not influence bias sampling.

Even though a broad range of particles size will yield the same mean velocity as the narrow size range, the narrow size range is recommended. The signal to noise ratio is better with the narrow range of particle sizes. Consequently the validation percentage is higher and even the validated data rate can be higher.

It is also recommended that corrections for bias sampling be applied to naturally seeded flows. Further experiments in a different apparatus should be conducted to verify earlier results (16) and to clearly demonstrate the existance of bias sampling. However, in the interim there is no evidence to suggest that corrections for sampling bias are not needed for LV systems operating in the individual realization mode.

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APPENDIX A

TABULATION OF DATA

TABLE A.1 Effect of Schmitt Trigger Level on SPC Reduction of LV Data Record for y = 0.0058 inches; Run Number BC-3*

Code Number	U_c (ft/sec)	U_B (ft/sec)	s_B (ft/sec)	N	Trigger Level (Volts)
540.4	0.1168	0.1359	0.0540	2026	0.35
540.5	0.1181	0.1373	0.0542	1839	0.40
540.6	0.1181	0.1371	0.0536	1746	0.45
540.7	0.1173	0.1355	0.0517	1516	0.55
540.9	0.1184	0.1362	0.0511	1312	0.60
540.10	0.1183	0.1369	0.0529	970	0.75
540.11	0.1178	0.1359	0.0512	753	0.90
540.12	0.1164	0.1339	0.0516	272	1.80
540.14	0.1173	0.1358	0.0532	403	1.40

* The total record time for this data record was 11 minutes 53 seconds.

TABLE A.2 Variation of Velocity with Distance from the Wall in Run Number 3100; 0-10 μm Seed.*

Code Number	y (inches)	U_c (ft/sec)	U_B (ft/sec)	s_B (ft/sec)	N
3101	0.0016	0.0368	0.0462	0.0232	80
3102	0.0025	0.0623	0.0709	0.0290	133
3103	0.00345	0.0947	0.1076	0.0395	265
3104	0.00495	0.1250	0.1420	0.0506	435
3105	0.0065	0.1531	0.1768	0.0688	652
3106	0.0075	0.1828	0.2104	0.0791	687

* Best estimate of pressure gradient was 0.122 lb_f/ft. at a temperature of 100^oF.

TABLE A.3 Variation of Velocity with Distance from the Wall in Run Number 3300; 0-10 μm Seed.*

Code Number	y (inches)	U_c (ft/sec)	U_B (ft/sec)	s_B (ft/sec)	N
3451	0.0030	0.0965	0.1105	0.0400	267
3452	0.0040	0.1140	0.1358	0.0566	163
34X3+	0.0049	0.1418	0.1634	----	---
34X4++	0.0068	0.1833	0.2165	----	---
34X5+++	0.0075	0.1969	0.2313	----	---
3456	0.0082	0.2236	0.2557	0.0902	706

* Best estimate of pressure gradient was 0.150 lb_f/ft. at a temperature of 98°F.

+ Average from five reductions at various detection levels; code numbers 3403 to 3443.

++Average from four reductions at various detection levels; code numbers 3464 to 3494.

+++Average from four reduction at various detection levels; code numbers 3405 to 3435.

TABLE A.4 Variation of Velocity with Distance from the Wall in Run Number 4000; 5-10 μm Seed.*

Code Number	y (inches)	U_c (ft/sec)	U_B (ft/sec)	s_B (ft/sec)	N
4151	0.0033	0.1144	0.1346	0.0541	175
4152	0.0042	0.1439	0.1680	0.0670	490
4153	0.0050	0.1604	0.1885	0.0773	427
4154	0.0065	0.1949	0.2292	0.0900	577
4155	0.0074	0.2104	0.2438	0.0905	645
4156	0.0082	0.2302	0.2706	0.1005	539

* Best estimate of pressure gradient was 0.154 lb_f/ft. at a temperature of 95°F.

TABLE A.5 Variation of Velocity with Distance from the Wall in Run Number 5000; 5-10 μm Seed.*

Code Number	y (inches)	U_c (ft/sec)	U_B (ft/sec)	s_B (ft/sec)	N
5011	0.0033	0.1201	0.1400	0.0559	361
5022	0.0041	0.1331	0.1528	0.0575	722
5033	0.0049	0.1543	0.1760	0.0643	893
5014	0.0065	0.1845	0.2095	0.0744	1011
5015	0.0074	0.2024	0.2307	0.0847	1121
5016	0.0082	0.2189	0.2448	0.0803	903

* Best estimate of the pressure gradient was 0.155 lb_f/ft. at a temperature of 76^{o}F.

TABLE A.6 Variation of Velocity with Distance from the Wall in Run Number 6000; 5-10 μm Seed.*

Code Number	y (inches)	U_c (ft/sec)	U_B (ft/sec)	s_B (ft/sec)	N
6001	0.0033	0.2467	0.2825	0.1024	826
6002	0.0041	0.2655	0.3036	0.1093	1697
6003	0.0049	0.2824	0.3239	0.1137	1969
6004	0.0066	0.3206	0.3637	0.1394	2158
6005	0.0074	0.3454	0.3873	0.1259	1534
6006	0.0082	0.3623	0.4077	0.1324	1353

* Best estimate of the pressure gradient was 0.157 lb_f/ft. at a temperature of 77½^{o}F.

APPENDIX B Bibliography of Publications Based on this Research

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Experimental Evaluation of Sampling Bias in Naturally Seeded Flows
Submitted for publication in the Proceedings of and for presentation at the Third International Workshop on Laser Velocimetry, Purdue University, West Lafayette, Indiana, July 11-13.